# A Review of Uranium Spoil and Mill Tailings Revegetation in the Western United States



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On page 5, column 2, lines 17-19 should read:

> indoor radon progeny levels (10 CFR 712 (Title 10, Code of Federal Regulations, part 712), Grand Junction Remedial Action Program).

On page 8, column 2, lines 7-9 below the equation should read:

> on (1) the effect of chemical and radiological concentrations of raw tailings on the amount of root penetration into the tailings, and (2) . . .

by the Civil Engineering Department, Colorado State University. Finally, recent field observations were evaluated for mining and milling operations in the southern Black Hills area, at Laguna and Grants, New Mexico, at Vitro tailings site, Salt Lake City, Utah, and from past field trips to Shirley Basin, near Casper, Wyoming.

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# A Review of Uranium Spoil and Mill Tailings Revegetation in the Western United States

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**Abstract**

The following aspects of uranium mine and mill tailings management are reviewed and discussed: (1) the history of the uranium remedial action program, (2) magnitude of the uranium spoils problem, (3) uranium deposits, mining, and milling, (4) status of reclamation, (5) problems in revegetation of uranium spoils and tailings, and (6) health and safety considerations.

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## MANAGEMENT IMPLICATIONS

The problems of reclaiming (via revegetation) uranium mill tailings piles and spoils are summarized as follows:

1. Reclamation acts in the western United States are relatively new. Consequently, there is little long-term experience with revegetation of uranium-mined (or of coal- and bentonite-mined) areas.
2. Uranium mill tailings piles are radioactive and contaminate the environment most commonly by wind and water erosion of radioactive particulates and by emission of radon gas and its progenies.
3. Indiscriminate revegetation programs create additional environmental problems, because plants absorb radionuclides and harmful trace elements and may pass them on to higher trophic levels within an ecosystem.
4. Plant growth and establishment are limited by climate and soil conditions. The problems of reclaiming abandoned piles and soils are greater because of the cost of overburden placement and lack of soil availability.
5. Revegetation may not provide long-term stabilization; instead, isolation and containment by rock cover may be the proper approach.

More information is needed on several aspects of revegetation in general:

1. Disturbed areas of mining activities, particularly the spoils and pits, must be appraised for their (1) radioactivity, (2) kind and depth of cover, (3) state of erosion, (4) degree and type of vegetative cover, and (5) status of radiological contamination.
2. Research has established that uptake of radionuclides and other contaminants are species dependent, but a great number of species need to be evaluated for their uptake characteristics.
3. Improved radiological safety and health procedures are needed in the revegetation program. Expertise developed by Argonne National Laboratory and U.S. Environmental Protection Agency (Office of Radiation Programs, Las Vegas Facility) will help to assess safety procedures.

Information is also needed on a site specific basis for the following aspects of revegetation:

1. The physical, chemical, and radiological properties of soil and soil substitutes (primarily overburden material) to be used as earth cover material and for control (from undisturbed areas surrounding the tailings piles), such as texture, water retention capacity, nutrient status, salinity-alkalinity, toxic trace elements, radionuclide concentration of natural uranium, thorium-230, radium-226, lead-210, and polonium-210.
2. The physical, chemical, nutrient, and radiological characteristics of tailings, such as texture, nutrient status, toxic trace elements; and radionuclide concentration of uranium-natural, thorium-230, radium-226, lead-210, and polonium-210.
3. The plant uptake of contaminants from earth covers over tailings not less than 3 m in depth, with less than 2 $pCi \cdot m^{-2} \cdot s^{-1}$ radon emission above background levels.
4. Availability of suitable soil and geologic cover materials. This kind of information is fundamental to revegetation of mill tailings piles and ponds.
5. The use of engineering methods to augment revegetation programs and help block radiation emissions. These methods are particularly important in quickly stabilizing abandoned mill tailings piles and in aiding quick revegetation.
6. Plant species which take up the least amount of radionuclides and other contaminants.
7. Contaminant levels of existing plants on tailings piles (such as what kinds of contaminants and how much uptake relative to tailings concentration, and areas of concentration within the plant).
8. Concentration levels of trace metals and radionuclides of plants growing on areas surrounding uranium tailings piles.
9. The effect of plant establishment on radon emission rates.
10. The uptake levels of radionuclides and other contaminants by animals inhabiting tailing piles, and their roles as vectors transporting radionuclides to the food chain.

## INTRODUCTION

Wastes from uranium mining and mill operation—the contaminated spoils, heap-leached piles, and mill tailings—are radioactive and potentially hazardous. Spoils are overburden and other geologic materials removed in gaining access to the ore material. Heap-leached piles and mill tailings are mineral refuse from leaching and milling operations. If these materials are not stabilized properly they can contaminate the biosphere.

Uranium waste management in the past dealt primarily with the geological and hydrological aspects of the waste disposal systems (Whicker 1978), although by law, reclamation must include revegetation. Substantially less effort has been made to understand the biological aspects of tailing management, particularly the interaction of vegetation and animals with contaminated spoils and tailings. Indiscriminate revegetation programs can create additional environmental problems, because plants and animals are potential vectors for radioactive and other toxic chemical elements.

Literature on uranium spoil and tailings reclamation in terms of revegetation before 1978 in the United States is very scarce. However, studies by the Los Alamos National Laboratory on the vegetative stabilization of inactive uranium mill tailings piles (Dreesen et al. 1978, Kelley 1979, and Reynolds et al. 1978) present concepts useful in revegetation efforts.

## MAGNITUDE OF THE URANIUM SPOILS PROBLEM—MINING LOCATIONS AND PRODUCTION IN THE UNITED STATES

Uranium ore has been milled in the United States since the late 1940's. Uranium mines have been operated in Alaska, Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. From 1948 to 1974, 270,100 tons of $U_3O_8$ (yellowcake) have been produced from 116,962,000 tons of ore in the United States; 75% has come from the states of New Mexico and Wyoming, 45% and 30% respectively. The Colorado Plateau (fig. 1) accounts for 66% of the produced and known \$10 (cost per pound of $U_3O_8$) reserves. The Wyoming Basins account for 23% and all others 11% of the reserves (U.S. Environmental Protection Agency 1977).

The bulk of the \$15 and \$30 uranium reserves (as of 1977) are also found in the Colorado Plateau and Wyoming Basins. New Mexico and Wyoming, based upon production records, contain most of the \$15 and \$30 reserves (New Mexico 48%, Wyoming 37%, respectively).

As of January 1, 1976, 22,911,000 acres were held by the uranium industry for mining and exploration. Of this land, 44% was in Wyoming, 18% in Utah, 16% in New Mexico, and 7% in Colorado. The land held in the remaining states ranged from 4% in Arizona to 0.1% in

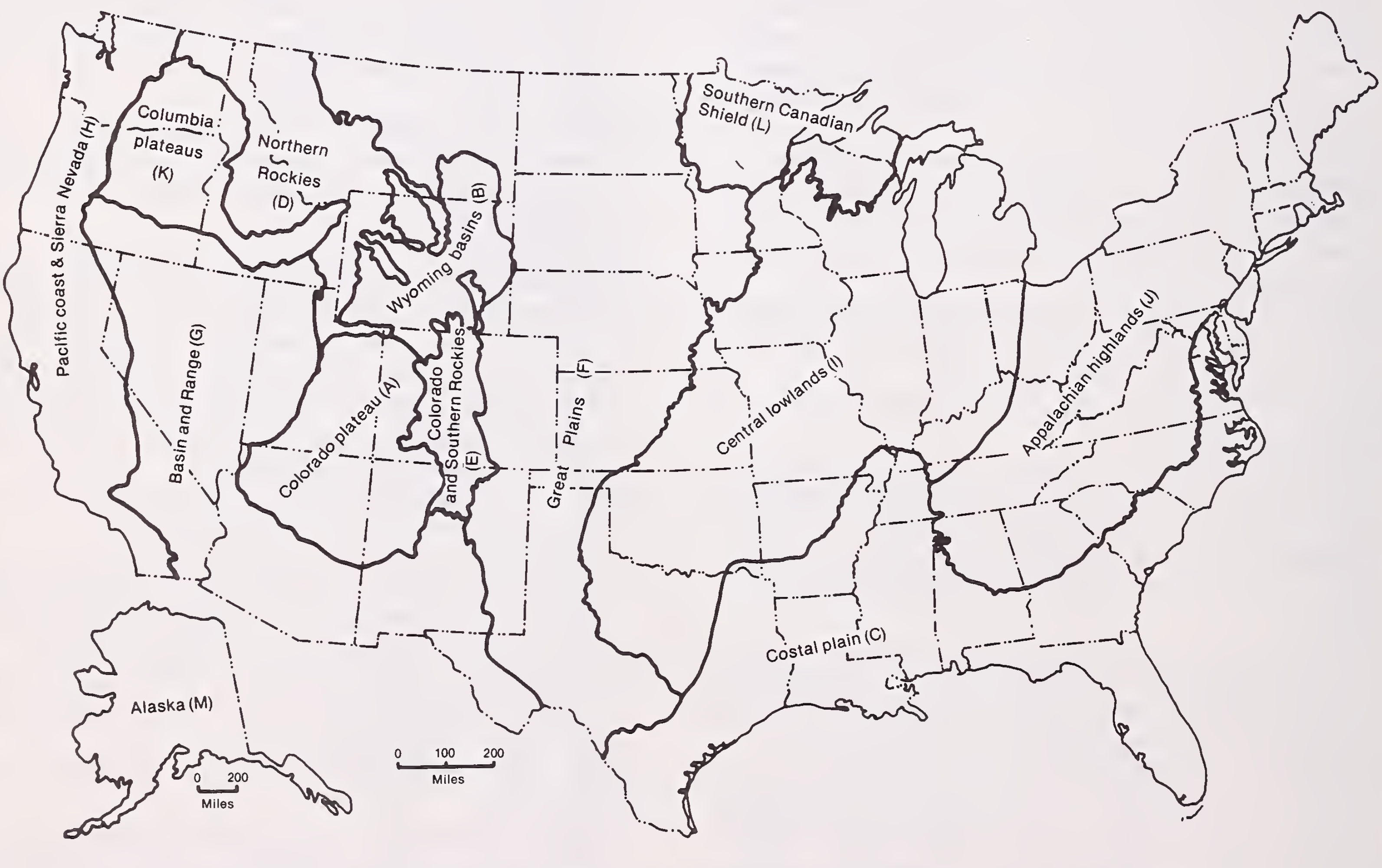


Figure 1.—Regional outlines used for the preliminary national uranium resources evaluation. (U.S. Energy Research and Development Administration 1976).

Oregon (U.S. Energy Research and Development Administration 1976). The most important uranium areas of the Western United States are shown in figure 2.

## Mining Waste

Uranium ore is recovered by both open pit and underground mining. Pit mining produces the most waste because the overburden is stripped away. For example, in 1974, 2,666,000 tons of uranium ore were mined from open pits in Wyoming. The waste produced was 104,046,000 tons of overburden and 2,984,000 tons of mill tailings. In contrast, 1,216,000 tons of ore from underground mines in Colorado produced 1,210,000 tons of tailings (U.S. Environmental Protection Agency 1977).

According to the U.S. Environmental Protection Agency (1977), 93% of the declared daily milling capacity was centered in the states of New Mexico (48%), Wyoming (33%), Colorado (6%), and Utah (6%). From 1965, the uranium processing rates steadily increased while the grade of ore and the percent of $U_3O_8$ recovered declined from 0.23% to 0.163%. Thus, as lower grades of ore are mined, the tailings per pound of yellowcake increase. In 1976, it was estimated that more than 9 million metric tons of tailings per year were put into tailing ponds by the domestic uranium industry. In addition, an equal or greater amount of waste milling solutions were also put into the ponds (Reed et al. 1976).

## Inactive Uranium Mills

Inactive mill sites in the West, their priorities for remedial action, and quantity of tailings are shown in the Final Generic Environmental Impact Statement on Uranium Milling (U.S. Nuclear Regulatory Commission 1980a). Their present or former mill owners are shown in U.S. Environmental Protection Agency (1977). These sites, identified under the remedial action program of Public Law 95-604, are a guide to selecting areas of revegetation research, because mill tailing piles from these sites were deactivated before criteria on reclamation procedures were standardized. Consequently, most of these sites were inadequately stabilized.

Finally, inventory surveys are needed in forested areas and have been requested by forest land managers for information on aerial extent of uranium exploration and mining disturbance, nature of disturbance, chemical (including trace metal) and radiological

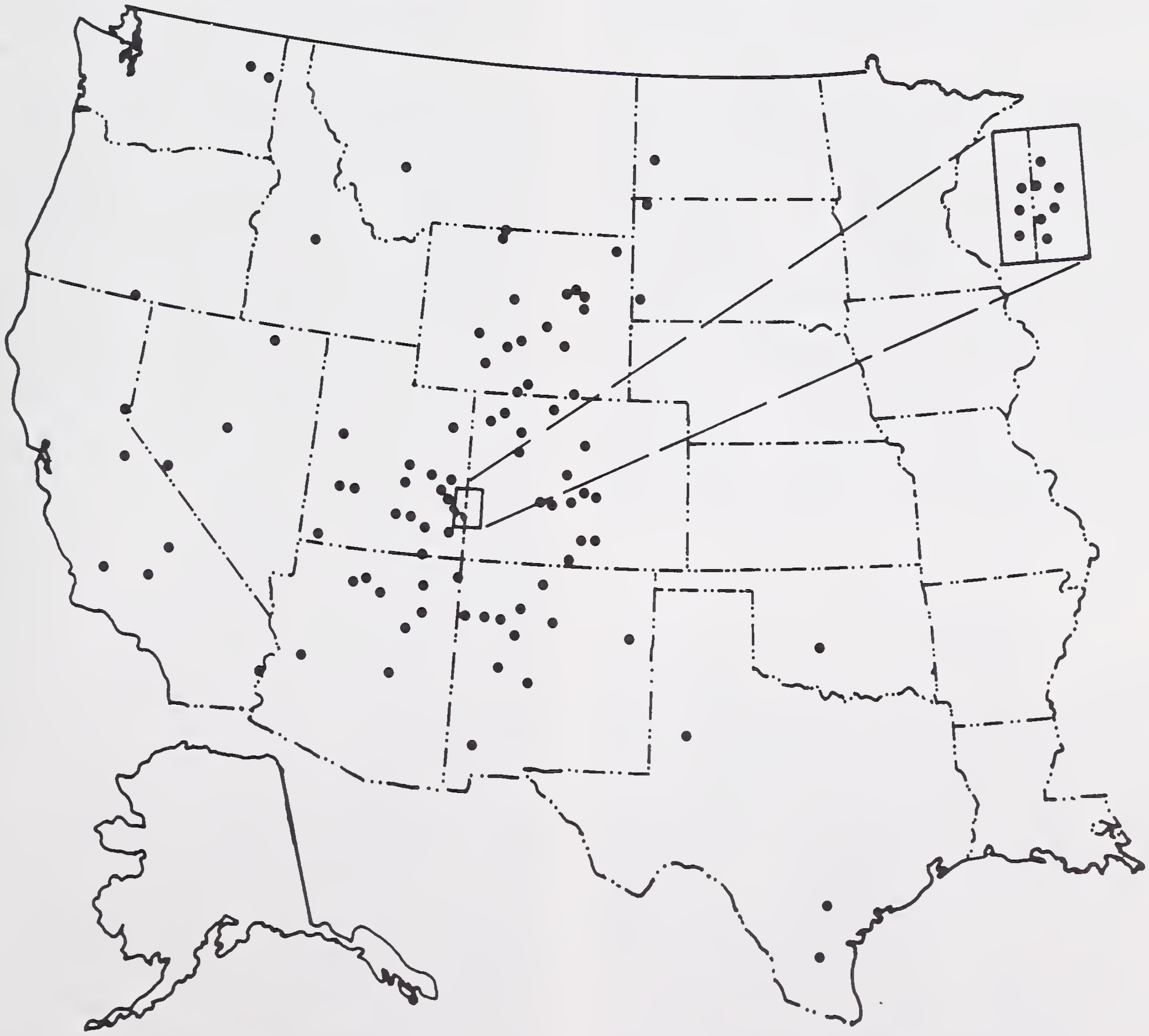

Figure 2.—Areas of uranium production in the western United States. (U.S. Energy Research and Development Administration 1976).

properties of the spoils, possible contamination to the biota and hydrology, and the kinds of remedial actions needed.

## CHARACTERISTICS OF DEPOSITS, MINING, AND TAILINGS

### Sandstone Deposits

Most of the uranium deposits in the Colorado Plateau and adjoining districts are stream-laid lenses of sandstone, dominantly in the Chinle, Shinarump, and Morrison Formations. Uranium occurs as coatings on sand grains or as fillings on cement in interstitial spaces, where it has been deposited by water. The uranium content of the deposits is in the order of 0.05% to 0.25% $U_3O_8$ (U.S. Nuclear Regulatory Commission 1979a). Uranium deposits also occur in the Wind River Formations in Gas Hills and Shirley Basin area in Wyoming, Lakota Formation in the Black Hills of South Dakota and elsewhere in other formations in lesser amounts. The stratigraphy and lithology of the overburden and host rocks, which may be important in revegetation research, are described in the "National Uranium Resource Evaluation Preliminary Report" (U.S. Energy Research and Development Administration 1976).

In general, the ore was formed by groundwater solutions that moved down the dip by gravity to a reducing environment, where the uranium was precipitated out of solution. These deposits are tabular or lenticular layers (pods), and deviations have the cross-section form of an erect crescent known as rolls. Because it is an extremely active material, uranium combines or is associated with many different compounds—sulphates, phosphates, vanadates, arsenical compounds, and carbonates (Reed et al. 1976, May 1973). In addition, uranium commonly occurs with carbonaceous matter (Dreesen et al. 1978) and many trace elements—selenium, molybdenum, lead, zinc, cobalt, nickel, copper, and others (Cannon 1962, Dreesen et al. 1978, Merritt 1971).

### Mining

Although in 1976, underground mining contributed roughly 49% of the total uranium ore produced in the United States,[2] many of these mines resulted from open pit mines that followed the major deposits underground. The ore bodies vary greatly in size from those containing only a few tons to those hundreds of meters across and containing millions of tons of ore. In the Shirley Basin area and the southern part of the Powder River Basin, Wyoming, and in the Ambrosia Lake District, New Mexico, groups of ore bodies and the intervening, thinner, mineralized zone extend intermittently from 8 to 10 km (Butler 1972).

Surface (open pit) mining may be done to depths of more than 150 m, whereas underground mining takes place at depths below 90 m (Reed et al. 1976). As in current coal strip mining, the surface soil is presumably stockpiled, if available, for later reclamation. Overburden from the initial excavation is placed on the surface and later used to backfill where mining has been completed. But, in most instances, the mined-out pits are so huge that it is not economically feasible to refill such holes (Schilling 1971). Thus, large amounts of material must be handled in mining and initial processing operations.

### Milling and Tailings Disposal

The ore is prepared in the mill by crushing, grinding, and blending. Sulfuric acid ($H_2SO_4$) is used in the leaching process. To oxidize the reduced uranium minerals, reagents such as $MnO_2$ and $NaClO_3$ are added, although aeration is often sufficient. Carbonate leaching is used when the carbonate content of the ore and its buffering capacity are so high that acid consumption would be prohibitive. Many purification processes are used to purify and concentrate yellowcake; during this process molybdenum, vanadium, selenium, iron, lead, nickel, zinc, cobalt, and many other impurities are removed and redistributed. The resulting tailings are highly mineralized. Finally, when radium-226 is separated from uranium, about 98.0% to 99.8% of the radium contained in the ore ends up in the tailings in solid form. Tailings consist of 80% sand and 20% slimes. The latter carry the bulk of the radium (Misaqi 1976; Moffett and Tellier 1977, 1978). There are 14 naturally occurring isotopes of uranium; because uranium-238 has a natural abundance of 99.283%, this isotope and its decay products are of prime concern in the tailings (Moffett and Tellier 1977). The important radioisotopes in terms of plant uptake are those which have a significant half-life in relation to the growing season of the plants. These radioisotopes are: uranium-238, uranium-234, thorium-230, radium-226, lead-210, and polonium-210. The tailings also emit a radioactive gas, radon-222, which can be transported long distances. The size of tailings piles reported and observed near Grants, N. Mex. may commonly vary from 2 to 37 ha (Dreesen et al. 1978); one active tailings pile had an average height in excess of 35 m and an area perhaps exceeding 60 ha.

The radon emanation from the decay of radium-226 in the tailings and other radioactive emissions create a long-term radiation risk which necessitates the definition of source terms for the tailings pile. Source term is defined as the quantity of radioactivity (in curies, for example) released in a specified period of time (U.S. Nuclear Regulatory Commission 1979b). For example, if the average radium concentration is known, the external gamma exposure rate over the tailings pile can be estimated. The radon emanation rate can also be estimated (Schiager 1974), and the depth of overburden

[2] *Klemenic, J. 1976. Analysis and trends in uranium supply. Presented at the Grand Junction Office Uranium Office Industry Seminar (October 19-20). U.S. Energy Research and Development Administration.*

necessary to reduce gamma and radon emanations can be estimated. Dreesen et al. (1978) emphasized the importance of recognizing source term variations due to distribution and variations in physical, chemical, and radiological properties of sand and slime of the tailings pile and overburden.

The current practice of discharging excess liquids from tailings ponds into drainages and injecting them into deep wells represents major environmental impacts (Reed et al. 1976, Kaufmann et al. 1976). If the hydrogeological, engineering, radiological protection, environmental, and economic aspects are favorable, disposal of tailings to mined-out portions of a mine is preferred. There is some promise for this method if the whole operation is planned in advance. However, there are difficulties. First, it is costly. Second, sands are satisfactory for backfill but the slimes are not. Third, slimes are more radioactive and contaminate hydrogeological systems. Fourth, if only slimes are retained in the tailings ponds, the structural and agricultural properties are not as good as the original tailings. This leads to a greater likelihood of waste retention system failure and a more difficult revegetation problem (International Atomic Energy Agency 1976).

## DEVELOPMENT AND STATUS OF RECLAMATION EFFORTS

Surface uranium-mined lands in the West have not been as extensively reclaimed as coal-mined lands. As recently as 1977, reclamation was limited to New Mexico and Wyoming (Evans et al. 1978). Furthermore, mining industry and government agency publications generally do not provide sufficient detailed information about the ecological aspects of mining disturbances.

In the United States, most of the uranium ore mined from the early 1940's through 1970 was processed for the Manhattan Engineering District and the Atomic Energy Commission (predecessor of the Energy Research and Development Administration) by private companies. When processing operations ceased for the U.S. Government, tons of uranium mill tailings remained. Mill operators were not aware of the potential radiation hazards to the public from exposure to the mill tailings. At that time, the general consensus was that the effects of the radioactivity on the public were minimal (U.S. Department of Energy 1979). Nevertheless, the possibility of health hazard from long-term exposure from windblown and water-transported tailings material were suspected.[3] Some companies made no attempt to stabilize the tailings after operations ceased, while others did so with varying degrees of success (Ford, Bacon and Davis Utah Inc. 1977h).

Until 1977, published studies on radiation levels on and in the vicinity of inactive processing and mill tailings sites generally were limited in scope. A report by Eadie et al. (1976) of outdoor radon air concentrations, radium-226 concentrations in the soil, and gamma exposure rates in the vicinity of uranium mines and mills throughout the Ambrosia Lake area in New Mexico indicated concentrations in excess of typical background levels. A better definition of background levels and a more thorough evaluation of specific source terms in the immediate Ambrosia Lake areas were suggested.

Similarly, gamma scan measurements on inactive uranium mill sites near Riverton, Wyo. (Douglas 1977) showed contamination above background levels at adjacent areas, presumably caused by wind erosion. However, results of limited well water and working level samples near the site did not exceed EPA's drinking water standard (U.S. Environmental Protection Agency 1976) or the Surgeon General's guidelines for indoor radon progeny levels (10 CFR 712 (Vol. 10, Code of Federal Regulations, page 712), Grand Junction Remedial Action Program).

In 1974 the Atomic Energy Commission recommended a generic and comprehensive study of all formerly active uranium mill tailings sites. Detailed engineering evaluations of many of these sites have been issued in a series of reports prepared by Ford, Bacon and Davis Utah Inc. (1976, 1977a-r inclusive, 1978) for the Energy Research and Development Administration. The reports include gamma surveys, radon concentration measurements, and measurements determining the extent of windblown soil, ground and surface water contamination. These surveys, in addition to radiological characterization, provide the following kinds of information which are pertinent to revegetation research: (1) present condition of the site, such as size of tailings pile, (2) whether the site is nonstabilized or stabilized, perhaps with earth cover, riprap, or grass cover, (3) tailings and soil characteristics, and (4) geology, hydrology, meteorology. In addition, Oak Ridge National Laboratory prepared a series of reports summarizing the radiological survey performed at these sites as a part of the assessments. Four from these series of reports are cited (Haywood et al. 1979, 1980a-c).

As a result of these surveys, Public Law 95-604, Uranium Mill Tailings Radiation Control Act of 1978, was enacted on November 8, 1978 (U.S. Department of Energy 1979). The law provides a program under Department of Energy to regulate uranium or thorium mill tailings processed at active and inactive operations to stabilize and control tailings in a safe and environmentally sound manner and to minimize or eliminate radiation hazards to the public.

Some of the rules pertinent to revegetation research on active and inactive uranium mill tailings piles as stated in 45 FR 65521 (Vol. 45, Federal Register, page 65521) are as follows:

1. Sufficient earth cover, not less than 3 m, should be placed over tailings to reduce radon exhalation from buried tailings to a calculated value of not more than $2\ pCi \cdot m^{-2} \cdot s^{-1}$ above natural background levels.

[3]*U.S. Atomic Energy Commission. 1963. A report of the Monticello mill tailing erosion control project, Monticello, Utah. Report No. RMO 3005, 31 p. U.S. Atomic Energy Commission, Grand Junction, Colo. Office*

2. A full, self-sustaining, vegetative cover should be established on the earth cover or a rock cover should be used to reduce to negligible amounts the potential for significant wind and water erosion of the earth cover.
3. In arid and semiarid regions, where it is unlikely vegetation will be full and self-sustaining, rock cover stabilization is mandatory.
4. Topographic features should provide good wind protection.
5. Embankment and cover slopes should be relatively flat after stabilization. Specific limits on final embankment slopes are not identified, however.

More recently Environmental Protection Agency's 40 CFR 192 (46 FR 2526, January 9, 1981), Proposed Disposal Standards for Inactive Uranium Processing Sites, Invitation for Comment, proposes an allowed tailings emission rate of 2 $pCi \cdot m^{-2} \cdot s^{-1}$ with soil cover recommended. No specific soil depth is specified. Also, a radium-226 concentration not exceeding 5 pCi/g in the earth cover 1 foot of surface, or in any 15 cm thickness below 1 foot, is specified (10 CFR 192, 45 FR 27367, April 28, 1980). Further, there are no formal regulations concerning disposal of mill tailings (U.S. Nuclear Regulatory Commission 1980b). The Environmental Protection Agency and Nuclear Regulatory Commission standards seem to be interim pending public review and promulgation of final standards.

Revegetation research on uranium mill tailings has only recently begun on some commercially owned operations (Reynolds et al. 1978, Dreesen et al. 1978, Kelley 1979) and on some Tennessee Valley Authority (1976, 1978, 1979) sites.

Unlike reclamation of surface mined lands, reclamation for underground operations must be delayed until normal mining operations cease because of the nature of the operations, the semipermanent nature of the structures involved, and the constant addition of material to the waste piles (Tennessee Valley Authority 1976). Reclamation may be further delayed by the dramatic climb in the price of uranium from $6 a pound in 1973 to $42 a pound since 1977, which has encouraged mining lower grade ores and reprocessing earlier discarded tailings. This rise in uranium price has delayed reclamation in Wyoming (Evans et al. 1978) and possibly in other states as well.

The U.S. Nuclear Regulatory Commission (1980a, 1980b, 1980c), in its environmental impact statement, did not address uranium mining impacts (e.g., nature of spoils and disturbance of land) because such an inclusion would have resulted in significant delay of improvements in current regulatory programs with respect to uranium milling. However, the U.S. Environmental Protection Agency, under the provisions of Public Law 95-604, is preparing a report on the environmental hazards of uranium mine wastes (U.S. Nuclear Regulatory Commission 1980b). Similarly, acceptable chemical concentration levels of plants grown on earth cover emplaced over uranium tailings piles are not proposed in the U.S. Nuclear Regulatory Commission's Final Generic Environmental Impact Statement (1980a) or specified in Appendix A of 10 CFR 40 (45 FR 65521, October 3, 1980). However, the overall guiding principle in selecting required levels of tailings isolation is to return the tailings site to a condition reasonably near those of surrounding environs (U.S. Nuclear Regulatory Commission 1980a, 1980c).

## PROBLEMS IN REVEGETATION OF URANIUM SPOILS AND TAILINGS

Revegetation of uranium mine spoils and tailings in the western United States must consider problems associated with (1) site characteristics, (2) compensating for climatic conditions, (3) spoils revegetation, (4) erosion, (5) biological interactions—penetration and uptake of contaminants by vegetation and animals, (6) tailings revegetation and cover, (7) riprap cover, (8) plant selection, and (9) shaping and sloping.

As in coal-mined land reclamation, the objectives of revegetation are to prevent erosion and to establish a sustainable ecosystem. But in terms of long-term disposal for 1,000 years, for example, uranium mine and mill waste may require isolation and containment, not revegetation (Dreesen et al. 1978, U.S. Nuclear Regulatory Commission 1980a).

### Site Characteristics

Although each area has its own characteristics, the arid, sandy plains and basins of the Colorado Plateau and Wyoming typify the conditions found at uranium-mined lands in the West. The sedimentary deposits where uranium is found most often are at lower elevation sandy plains, basins, or plateaus. Surface soils are usually poorly developed in both physical and chemical properties, are shallow, and have all the problems found in revegetating and reclaiming coal strip mine spoils (i.e., limited moisture, salinity, alkalinity, acidity, toxic constituents, deficiency of nitrogen and/or phosphorus, blowing sand, and animal browsing and grazing) (Kelley 1979, National Academy of Sciences 1974).

### Compensating for Climatic Limitations

The prevailing climate creates an undependable supply of moisture for revegetation. On the Colorado Plateau, annual precipitation ranges from 12.7 cm in the deserts to 45.7 cm at high altitudes (Cannon 1962); a range of 18 to 25 cm is reported (May 1973) for mining areas in the western United States. The areas are subjected to high evaporation and sublimation losses, high temperatures, and dessicating winds. Surface and ground water supplies generally are not available. Because uranium and coal occur in the same areas (Evans et al. 1978) revegetation techniques for coal-mined areas which deal with the problems of moisture supply (USDA Forest Service 1979a, 1979b) should apply to uranium areas.

Treatments that augment water infiltration, and moisture retention and detention should noticeably improve revegetation programs. Well-known range improvement practices such as surface pitting, mulching with wood chips, straw, asphalt materials, and snow fencing may be employed with varying degrees of success because water is limited in many uranium areas.

Irrigation may be an impractical method of promoting revegetation. More important, the cessation of irrigation often resulted in extensive mortality of established vegetation and promoted the upward movement of radioactive elements and other potentially toxic elements such as selenium and molybdenum (Dreesen et al. 1978, Markos 1979). Further, pitted surfaces, water harvesting trenches, and other water collection structures may become collective centers of radioactive, alkali, and other salts similar to those seen in saline-alkali areas of bentonite and coal deposits (Sandoval and Gould 1978). Hence, one of the major goals of vegetational stabilization studies may have to be the determination of environmental factors harmful to establishing vegetation without irrigation (Dreesen et al. 1978, Kelley 1979).

### Spoils Revegetation

From a geographical, ecological, or geological standpoint, the revegetation of uncontaminated uranium mine spoils should not pose problems unusually different from coal mine spoils. The problems are site specific and usually can be resolved by selective emplacement of top soils and overburden (Dreesen et al. 1978, Kelley 1979, Reynolds et al. 1978).

Uranium spoils samples from each site must be analyzed to determine mineralogy, nutrient status, texture, and pH, before revegetation can begin. The same techniques for dealing with physical and chemical characteristics of coal spoils can be used for uranium spoils (USDA Forest Service 1979b, Schaller and Sutton 1978). However, if the spoils are contaminated with radionuclides and their progenies or with potentially toxic trace elements, in greater amounts than those found in adjoining lands, these materials must be handled and treated in the same mannner as mill tailings and analyzed for these contaminants at appropriate laboratories. Vegetation or contaminated spoil piles possibly could absorb these elements at levels toxic to grazing animals or could present a public health problem similar to tailings piles. However, unless the spoils are contaminated by radioactivity or chemically toxic elements, priority should be given to research on mill tailings waste.

### Erosion

Erosion by wind and water must first be stabilized before revegetation can begin. Wind and water erosion are obvious in uranium waste areas where maintenance has been discontinued (U.S. Environmental Protection Agency 1973, Douglas 1977). There is extensive literature on wind and water erosion.

Studies on wind erosion by Chepil (1945) are classics. Erosion protection measures for western coal-mined land reclamation are summarized by Verma and Thames (1978). Thames et al. (1974) measured runoff from a disturbed, coal-mined watershed in Arizona. Runoff and erosion characteristics from disturbed coal-mined land were estimated from simulated plot studies in North Dakota by Gilley et al. (1977), and in Wyoming by Lusby and Toy (1976). Similarly, infiltration studies on coal spoils were reported by Farmer and Richardson (1976), Rahn (1975), and Yamamoto (1979). However, these findings are based on research done on experimental areas or using scale models. No data are available on actual disturbed coal-mined lands or uranium mill tailings and spoil piles.

Available information on the movement and characteristics of radioactive elements of airborne particles is increasing (Breslin and Glauberman 1970, Kalkwarf 1979, Eadie et al. 1976, Douglas 1977, Travis et al. 1979). As more data and knowledge are accumulated for wind erosion, more research is also needed on plant-slope stability relationships because mine-waste embankments have a history of instability (USDA Forest Service 1979c).

Technology to control sheet and rill erosion is already available. For example, Abt and Ruff (1978) suggested using the Universal Soil Loss Equation to control or eliminate excessive losses from water erosion after mining is completed. Similarly, the Wind Soil Loss Equation (Utah Water Research Laboratory 1976) also can be used, because the same practices used to control water erosion will also control wind erosion and vice versa (Shepherd and Nelson 1978). These equations developed for agricultural and highway lands respectively may not consistently predict mine spoil losses (Gee et al. 1978), but they represent the current state-of-the-art and contain general principles that should apply to all sites.

### Biological Interactions—Penetration and Uptake of Contaminants by Vegetation and Animals

More information and research are needed to assess interactions of plants and animals with uranium mill tailings or contaminated spoils over an extended period of time. Whicker (1978) emphasized the role of plants and animals in the long-term erosion process and the penetration and uptake of radionuclides by biota on uranium tailings piles.

Dreesen et al. (1978) discussed the potential contaminants associated with uranium mill tailings and stressed the significance of contaminant uptake by plants to the food chain. They also questioned the duration of plant cover over long periods of time and suggested the use of riprap cover to augment the vegetation cover.

#### Effects of Plants and Animals on Erosion of Tailings Piles

Current reclamation plans for radioactive uranium tailings must provide sufficient earth cover, not less

than 3 m deep, to reduce direct gamma radiation to essentially background levels and radon emanation to less than 2 $pCi \cdot m^{-2} \cdot s^{-1}$ above natural background levels (10 CFR 40, 150 in 45 FR 65521, Oct. 3, 1980). The current practice is to cover the tailing surface with a layer of clay, followed by overburden, then topsoil covered with planted/seeded vegetation (Scarano and Linehan 1978). However, vegetation does not necessarily assure long-term stability. Subtle changes in soil and vegetation caused by animals could affect the long-term soil dynamics (Whicker 1978). For example, heavy grazing by cattle, in the natural pastures of short-grass plains of north-central Colorado, may be causing the loss of about 30.5 cm of surface soil in 1,000 years (Alldredge and Whicker 1972). Under a light grazing regime, net soil accumulations of about 35.6 cm per 1,000 years were suggested in adjacent pastures—a net difference of about 66.1 cm of soil between the two types of grazing. These changes may well influence plant survival and vigor.

Plants and animals, particularly burrowing animals, generally cause pulverization, granulation, and transfer of large amounts of soil. Termites, for example, are reported to have a beneficial effect on the development of strip-mine spoils (Ettershank et al. 1978). Similarly, the action of microbiological organisms on plant growth need to be examined (Lindsey et al. 1977). Also the amount of soil transported to the surface by ants (Uresk and Cline 1978) and gophers (Ellison 1946, Seton 1929) may affect erosion. Rodents and plants can also reduce soil water potentials significantly (Soholt et al. 1976). Also, mule deer (Arthur and Alldredge 1979) and cattle (Wijk and Braams 1960) probably ingest significant amounts of soil over time. Finally, rodents, ungulates, and insects often severely consume and destroy newly planted vegetation so as to nullify revegetation attempts.

Proper consideration should be given to these complex ecological interactions that may have profound long-term effects on stability of protective covers. Soil and vegetation can be protected using control measures, such as fencing, repellants, use of less palatable species (USDA Forest Service 1979a, 1979b). However, more data and experience are needed to determine performance standards such as erosion rates and the time needed to adequately monitor the sites after mining.

### Biological Penetration, Uptake, and Transport of Contaminants from Tailings Piles

Studies by Dreesen et al. (1978), Moffett and Tellier (1977), Vavilox et al. (1977), Cataldo et al. (1977), Ford, Bacon and Davis Utah Inc. (1978), and others have established that plant root penetration into the spoils and tailings, and uptake of radionuclides and other toxic chemical elements, particularly from covered and/or uncovered tailings piles and ponds, may constitute a significant food chain transport mechanism.

The uptake of radionuclides and trace elements has been examined to determine if these elements are being concentrated in plants above background levels (Dreesen et al. 1978, Moffett and Tellier 1977, Rickard et al. 1977). However, the mechanism of plant uptake of contaminants mixed into the spoil is probably different from uptake by plants or overburden placed over a tailings surface. The magnitude of uptake is usually expressed by the concentration ratio (CR):

$$CR = \frac{\text{Ci/g dry weight plant material}}{\text{Ci/g dry weight soil}}.$$

Uranium amended (uranylnitrate) lysimeter experiments at Hanford repository have shown, for example, that uranium concentration in plant materials appear to vary independently of soil concentration (Rickard et al. 1977). But more data utilizing actual uranium mill tailings are needed. Moreover, information is needed on (1) the effect of chemical and radiological concentrations on the amount of root penetration into the tailings of raw tailings, and (2) effect of overburden or soil depth on plant root penetration into the tailings and uptake of contaminants. Further, detailed information on trace metal and radionuclide concentrations in plants growing on lands adjoining the tailings pile areas is essential to determine acceptable levels of chemical constituents of plants growing over tailings piles.

Further studies are needed to examine soil-to-root pathway, foliar pathways (Romney et al. 1973), and surface contamination. Studies of influences on plant uptake (Cataldo et al. 1977) indicate that uptake is dependent on the plant species (Dreesen et al. 1978). The reasons for this variability need to be thoroughly investigated. Previous geobotanical work must also be reviewed. For example, the absorption characteristics of *Astragalus* vary considerably in associated selenium absorption (Cannon 1962). Studies at Rockwell Hanford Operations by Battelle Pacific Northwest Laboratories (Cataldo et al. 1977, Schreckhise et al. 1979, Cline and Uresk 1977) indicate that the uptake characteristics of cheatgrass (*Bromus tectorum*) and Russian thistle (*Salsola kali*) need further study. Cheatgrass is an early season competitor for soil moisture and nutrients; therefore, a good stand of cheatgrass is able to reduce the amount of deep-rooted Russian thistle that germinates later in the year (Cline and Uresk 1979). Also, Markos (1979) suggests that more geochemical studies of the identity, quantity, and profile distribution of salts and radionuclides are needed in conjunction with plant uptake investigations. The possible hazards posed by toxic trace elements (U, V, Mo, Se, As, Pb, Cu, Ni, Co, Zn) enriched in tailings should not be ignored (Dreesen et al. 1978, Merritt 1971). Molybdenum poisoning has been diagnosed in cattle grazing near uranium mines in Texas (Dollahite et al. 1972), and uranium mills in North Dakota (State of North Dakota 1978) and Colorado (Chappel 1975). Mortality of sheep, grazing in a uranium ore outcrop area in New Mexico, has been tentatively linked to selenium toxicity (Rapaport 1963). Forage plants containing high selenium concentrations can cause chronic selenium poisoning in two forms—blind staggers and alkali

disease. Plants with extremely high selenium concentration can cause acute selenium poisoning (Rosenfield and Beath 1964).

Because element concentrations in plant tissues may change with plant age (Johansen 1978, Cataldo et al. 1977) changes in sampling schemes and protective measures may be necessary. Also, data on the area of concentration within the plant (stem, foliage, roots, seeds) of radionuclides and other toxic chemicals are needed to help understand the food chain cycling process (Schreckhise and Cline 1980). The effect of vegetation on radon exhalation has not been demonstrated clearly, either. For example, vacant root channels or root penetrations could provide additional pathways for radon diffusion to the surface (Wullstein 1978).

Some plant species may even provide a means for monitoring nuclear plant sites or mill wastes for chronically emitted amounts of low-level, ionizing radiation. Research by Campbell and Rechel (1979) on somatic mutations in relation to reproductive integrity and pollen viability of *Tradescantia* suggests that such an alternative is possible.

The presence of carbonaceous matter has been reported in many uranium ore deposits (Squyres, 1970; Granger, 1963). These organic constituents may complex trace metals dissolved from tailings or originally may contain the trace elements in the ore matrix that dissolved after milling. Such organo-metallic species may play a significant role in the transport, uptake, and toxicity of trace elements from mill tailings (Dreesen et al. 1978). Further, the action of microbes in tailings may form volatile organo-metallic species (Wood, 1974). Because organic materials appear to have a key role in the enrichment of trace elements in ores, it should be expected that these organic constituents could significantly influence the release of trace elements from tailings.

Prairie dog mounds and rabbit and coyote droppings have been observed at tailings sites. Animal use of these sites indicates that studies are needed on the role of burrowing and other animals in (1) radon diffusion and (2) the uptake and transport of radionuclides (Rogers and Rickard 1977). Studies must evaluate the radioactive levels of animals inhabiting radioactive waste areas and their role as vectors transporting radionuclides to people (Schreckhise et al. 1979).

## Tailings Revegetation and Cover

The most practical and effective means of promoting vegetation and blocking the release of radioactive particulates and radon is to cover the tailings with earth. A minimum cover thickness of 3 m is specified by Appendix A of 10 CFR 40. According to U.S. Nuclear Regulatory Commission (1980c), this depth of cover is believed to provide a long enough diffusion path so that substantial amounts of radon and its solid daughters can be made to decay before escaping to the surface. But there are many uncertainties about long-term (i.e. 1,000 years) cover protection. The U.S. Nuclear Regulatory Commission believes that the minimum cover requirement provides a desirable margin of physical isolation of the tailings in the face of these uncertainties and will avoid undue reliance on special materials or maintenance of special conditions (U.S. Nuclear Regulatory Commission 1980a).

Judgment and experience are required to evaluate the many properties (including soil properties, emanating power, and vegetation cover) controlling radon exhalation from earth cover materials (U.S. Nuclear Regulatory Commission 1980a, 1980c). Moreover, the rules for tailings disposal are not final, and the cost of overburden placement over tailings is very expensive. Much research has gone into a search for cover material technologies that are economical, effective, and reduce the thickness of cover required. Three meters of earth cover may not be sufficient to reduce radon exhalation to 2 $pCi \cdot m^{-2} \cdot s^{-1}$ on a site specific basis. Further, revegetation cover and density is seldom as complete or permanent as desired. Therefore, engineering, chemical, or other treatments should be used to effectively complement the earth cover. Several different treatments on tailings are possible.

### No Cover: No Soil Amendments, No Irrigation

In the arid to semiarid regions of the Southwest and the northern Great Plains, only a sparse growth of invading species is likely to become established if no artificial revegetation techniques are used (Dreesen et al. 1978, U.S. Environmental Protection Agency 1973).

Aridity, high salts concentration, and extremely low pH (or, conversely, extremely high pH resulting from chemical treatment of the ore) will hinder plant establishment and growth. The tailings will be subject to wind and water erosion.[4]

### No Cover: Seeding, Soil Amendment, Irrigation

At Edgemont, S. Dak., two tailings plots were neutralized with lime application, fertilized with manure and ammonium nitrate, and seeded with rye grass, red clover, and a species known locally as fireweed (U.S. Environmental Protection Agency 1973). One plot was watered by a sprinkler system once every three days (amount of water used was not reported); the other plot was not watered. Aside from site stabilization, the consequences of plant uptake of radioactive materials was not considered at that time.

Revegetation failed on both plots. It was believed that the lack of good soil base and the late planting date caused the failures. However, fireweed, although

[4] *Abandoned (and some active) tailings and mill area spoils in the plains observed in New Mexico and South Dakota were dustier than those observed in the forested uplands. However, an abandoned tailings bench in the uplands of Mount Taylor District in Grants, New Mexico, showed very little sign of erosion even without any vegetation cover. No dust was observed, even under very windy conditions, from the porous sandy loam surface which showed very little sign of compaction. (Personal observation by the author.)*

sparse, did germinate on both plots. The fact that fireweed could grow was considered positive, because fireweed could provide a mulch source for the establishment of natural grass.

Generally, irrigation with soil amendment is expected to enhance establishment of vegetation, because toxic materials are leached from the soil. However, plant communities established by irrigation may not survive once irrigation is stopped. Moreover, irrigation may increase salt accumulation, especially in arid regions (Thorne and Peterson 1949).

### No Cover: Seeding, Soil Amendment, Wet Climate

In wet, temperate areas, such as at Elliot Lake, Ontario, species of grass, legumes, and annuals were seeded and successfully established by neutralizing acidity and adding fertilizer to compensate for the low nutrient status of the tailings (Murray and Moffett 1977). No supplemental organic matter or topsoil were involved. Moffett and Tellier's (1977) study on the uptake of radioisotopes by creeping red fescue (*Festuca rubra* L.), reed canary grass (*Phalaris arundinacea* L.), redtop (*Agrostis alba* L.), and timothy (*Phleum pratensis* L.) showed that uranium and radium-226 concentrations were higher in the grasses from the tailings than those from the control (potting soil). The uranium concentration of 0.030 mg/g, from the tailings in grass tissue, was not considered a hazard to any life form because of uranium's low specific activity. Specific activity is defined as the number of curies or the concentration of radioactivity per unit of mass or volume (Cember 1969). In contrast, the concentration of radium-226 in grass tissue (5.48 pCi/g) from tailing's was more than 20 times the concentration found in grass tissue (0.24 pCi/g) from the potting soil control. Radium-226 has an extremely high specific activity and, therefore, a very low maximum permissable concentration, for example, in water. Nevertheless, the concentration ratio of radium-226 for grass grown on tailings was 0.03, a value considered as biologically insignificant.

### Shallow Soil Cover

The term shallow soil cover is defined in this report as any soil or earth cover less than 1 m deep. As required by law, covering the tailings with surface soil (stockpiled during initial mining activities) still seems to be the most practical way to obtain a suitable growth medium. However, sandstone overburden materials with fairly high infiltration rates and good water retention (sandy clay loam and clay loam) were also favorable for plant establishment (Dreesen et al. 1978, Reynolds et al. 1978, Kelley 1979). These moderately coarse textured soils also had favorable nutrient concentrations. However, without supplementary irrigation, it is extremely difficult to establish vegetation in arid and semiarid climates.

Soil covers not only serve as growth media but as barriers to block or reduce radon emanation, radioactive particulates, and gamma ray emission. However, in most areas, without irrigation, survival of seedlings is poor, and the upward migration of salts may further limit survival. Further, shallow covers, defined as depths of cover less than about 60 cm (Dreesen et al. 1978, Vavilov et al. 1977), to moderately deep, at about 1 m (Macbeth et al. 1979, Dreesen et al. 1978), will not block radon gas emissions. But an earth cover of 61 cm can reduce gamma ray exposure to natural background levels; 610 cm would be required to reduce radon flux to the normal background levels (Schiager 1974). Predictive models by Clements et al. (1978) correlated well with actual measurements by Dreesen et al. (1978). These barrier soil depths depend on the soil density and moisture content (Rogers et al. 1979, Nelson et al. 1980).

**Improvements to shallow soil cover.**—In uranium mill tailings revegetation, the cover of topsoil and other earth materials placed over the tailings must enhance vegetation growth and provide a barrier to radiological emissions above background levels. The requirement for a 3 m minimum thickness cover of earth material is not considered by mining industry as a totally satisfactory solution based on economics and the availability of cover material (U.S. Nuclear Regulatory Commission 1980b). Thus studies have continued on shallow soil covers in seeking economical, effective methods to stabilize tailings piles and to isolate radioactive elements from the biosphere.

Several techniques should be considered to augment shallow soil covers. Some of these techniques are particularly useful in providing quick temporary stabilization.

1. Place a layer of coarse textured overburden material over the tailings surface to break capillary attraction of tailings fluid (Macbeth et al. 1979).
2. Place a layer of clay cap, with high exchange capacity, over the tailings surface to absorb contaminants and also to provide a physical barrier to upward migrations of ions (Macbeth et al. 1979, Gee et al. 1980). Moisture in the soil cover is very important. With materials, such as clays, which have been wetted, radon can be attenuated to the prescribed flux limit with relatively thin layers of cap material (U.S. Nuclear Regulatory Commission 1980a).
3. Place a layer of riprap cover mixed with soil over the tailings to conserve soil moisture, trap eolian particles, trap precipitation, protect seedlings from wind damage, and inhibit soil erosion (Dreesen et al. 1978).
4. Establish water harvesting structures to collect rainfall, thereby increasing available soil moisture (Packer and Aldon 1978).
5. Cover the raw tailings with plastic membranes (Macbeth et al. 1979).
6. Apply an asphalt emulsion on tailing surface (Hartley et al. 1979, Havens and Dean 1969).

7. Riprap cover to suit the situation.
8. Fertilize or treat with lime to improve plant growth.
9. Install snow fencing to increase water accumulation and retention.
10. Fence the area to exclude grazing animals.
11. Use cobbles (large stones) as biobarriers to exclude plant roots and ants and other burrowing animals, to prevent them from translocating contaminated materials to the surface (Cline et al. 1980). A 3-m earth cover may not be a barrier to some species of harvester ants (e.g. *Pogonomyres occidentalis*) which bore that deep (Headlee and Dean 1980).
12. Use resinous adhesives, lignosulfanates, elastomeric polymers, milk of lime, mixtures of wax, tar and pitch, potassium and sodium silicates, or neoprene emulsions to form crust on top of tailings surfaces (Havens and Dean 1969, Dean and Havens 1971).
13. Use root toxins together with cobbles to inhibit downward root extension (Cline 1979).

### Shallow Soil Cover With Irrigation

Some problems associated with irrigation (e.g. the upward movement of contaminants as production of vegetation increases) may be offset to some degree by the deep leaching of ions below the rooting zone with irrigations. Also, survival of vegetation after irrigation is stopped may be a problem. Procedures to improve shallow soil cover without irrigation can be applied to avoid this problem.

### Deep Soil and Overburden Cover

Information currently available indicates that deep cover over radionuclides is the most acceptable treatment (Dreesen et al. 1978; U.S. Nuclear Regulatory Commission 1979a, 1980a; Macbeth et al. 1979) as well as the one required by law.

The primary restraint to deep cover is the cost of the covering operation, which includes excavating, hauling, backfilling, and compacting. The cost rises if suitable material is not available on site, and varies by the volume and area of the tailings area and the strength of the radioactivity. Thus, one of the goals of research is to determine the depth of cover needed to suppress radon emission to a desired level. The advantages of deep soil cover include: (1) greater reduction of radon gas emissions, (2) reduction in need for long-term monitoring, (3) more and easier treatment options between the tailings surface and ground surface, and (4) increase in soil moisture storage capacity.

Natural invasion of surrounding plant species would be slow in the beginning, but individual plants will last longer once a plant community is established. However, some deep rooted plants, such as Russian thistle, may invade the plot. Generally, if the cover is deep enough to prevent plant roots and moisture from penetrating into the tailings, little contaminant uptake should result. Even so, the problem of upward migration of contaminants remains because the upward travel distance of salts over time has not been established. This is a continuous process as suggested by salt distribution with depth and the constant regeneration of salts (Markos 1979). Further, radium-226 transport by vegetation to the surface increases sharply with time (Vavilov et al. 1977), because soil and plant aging significantly increases the ion uptake (Cline and Uresk 1977). Thus, a deep soil cover may not inhibit the upward movement of contaminants over time.

**Improvements to deep soil and overburden cover.—** If water is available for irrigation, plant establishment improves. Therefore, techniques that limit deep percolation should be devised. Other techniques discussed under improvements to shallow cover should be considered also.

### Riprap Cover

The long-term sustenance of vegetation cover is questioned by many workers (Dreesen et al. 1978). They recommend the use of riprap as a final treatment. Riprap, in addition to providing protection against erosion, collects eolian soil particles and thus provides a more favorable plant habitat for vegetation to grow between rocks.

## Plant Selection

The approaches used to obtain ecologically adapted plants for reclamation of uranium-mined lands, with some exceptions, are similar to those for coal-mine lands. First, any species used must be able to withstand arid or semiarid conditions found at the uranium or coal basins. Second, selected species must be adapted to the edaphic factors of low or high pH, nutrient deficiencies, and chemical imbalances. Species selected for uranium spoil or tailings also must be able to withstand the effects of radioactivity and trace elements, and still limit their uptake of these elements. It is also desirable for plants to have root systems which limit the upward emanation of radon through the soil. Third, the plants must fit the reclamation objectives of cover, productivity, habitat for birds or animals, esthetic values, etc. The task of plant selection, perhaps the most important in revegetation research, is difficult because the chemical and radiological properties differ among sites, and ion uptake varies among species (Dreesen et al. 1978).

The most simple and effective selection method seems to be the use of species that have invaded the spoil and tailings pile. Dreesen et al. (1978) noted three plant species (*Atriplex canescens*, *Kochia scoparia*, and *Sitanion hystrix*) that successfully invaded tailings piles at Grants, N. Mex. Reynolds et al. (1978), Kelley (1979), and others (Thames 1977) also investigated various plant species which should be considered for tailings revegetation in the Southwest. Plant species

that have commonly invaded uranium overburden piles in Wyoming were noted by May (1973). However, the concentration ratios (e.g. of U, V, Ra, Se, Mo, As, Co, etc.) for many of these plants have not been determined as yet.

According to geobotanists (Cannon 1962, Froelich and Kleinhampl 1962, Kleinhampl and Koteff 1962, Kleinhampl 1962), the distribution of plants in the environment of the uranium deposit is controlled by the presence of selenium, sulfur, and other associated trace elements. On the flat beds, at lower altitudes, of the Colorado Plateau, there is a correlation between major plant zones and stratigraphic units (Cannon 1962). Kuchler (1964) also described potential natural communities. Knowledge of the mechanisms for natural formation of plant associations in these mineralized regions may provide clues to plant species selection for these areas. The experiences of Ludeke (1977), Nielson et al. (1972, 1973, 1978), and Peterson and Nielson (1973) in mill tailings revegetation provide useful information for plant selection in mine tailings ponds. Selection of plants unpalatable to animals, which fit the criteria of adaptability and low uptake of contaminants, also should be considered.

Field experiments in selecting and establishing plant species are best conducted at inactive sites (Dreesen et al. 1978, Nielson and Peterson 1978). On active ponds, slurries are constantly transported and flooding occurs at regular intervals; therefore, these ponds generally are not practical for planting experiments. Greenhouse, pot lysimeter, and growth chamber experiments are necessary and should be integrated, for example, in (1) expediting plant selection experiments, (2) testing theories of contaminant uptake or leaching for testing under field conditions, (3) providing uncontaminated "control" measurements, and (4) conducting bioassays.

### Shaping and Sloping

One of the most important factors influencing the containment capability of tailings piles is the degree to which ground, surface water, and wind contact the tailings material and subsequently transport the radionuclides, radon gas, and trace elements. Shaping and sloping both the tailings and the cover strengthens the stability of the waste pile by controlling the intake and loss of water from the pile and ensures a degree of permanence that vegetation sometimes cannot provide. This also improves the establishment of vegetation.

Riprap treatment has been very effective in reducing wind and water erosion and trapping eolian soil particles, which form a microhabitat for the vegetation. Therefore, this treatment and its modification should be considered in site preparation studies.

Several typical questions have to be answered: Will the depressions of the tailings surface be retained? If so, how will the water level be controlled? If not, how will the depression be filled and will the final surface be flat or contoured to a slightly domed shape? If contoured, what slope angles are favorable? Will the embankment side slopes be flattened? Are there outside sources of surface runoff into the pile? Are there internal sources of recharge through hydrogeologic connections? How is the concept of riprap treatment with sloping and shaping best utilized? What kinds and combinations of vegetation, grasses, shrubs, or trees will promote the stabilization of embankment slopes? What is the effect of vegetation on the ground water found in inactive piles and its recharge?

The answers depend on the actual conditions at the site, but all decisions should be aimed at the objectives of reducing wind and water erosion, and maximizing the stability of the embankment.

## HEALTH CONSIDERATIONS

In 1970, it was accepted that waste tailings with less than 0.05% uranium content were potentially harmful and should not be used for construction material (U.S. Environmental Protection Agency 1977). Moreover, before 1976, mill operators were not required to monitor radon levels (U.S. Nuclear Regulatory Commission 1979a). On November 8, 1978, Public Law 95-604 was enacted authorizing public funds to reclaim exposed, abandoned tailings. Thus the recognition and evaluation of possible radiological health hazards associated with ore and waste products (Ford, Bacon and Davis Utah Inc. 1976, 1977a-r inclusive; Haywood et al. 1979, 1980a-c) is really not too far from its beginning.

### Pathways of Radiation

Three pathways can result in radiation exposure to humans, according to present views.

1. Whole body gamma irradiation directly from the pile itself or from the deposition of windborne material.
2. Deposition of radionuclides in the body or in an organ of the body because of direct ingestion of mill tailings material or of water or food that has been contaminated by the tailings material.
3. Deposition of radionuclides in the body or in an organ because of inhalation, primarily of alpha irradiation into the pulmonary region. Deposition in other areas of the body can also occur as material circulates from the pulmonary region through the bloodstream.

The consensus of literature is that the radiation dose to the pulmonary region is the most critical pathway (U.S. Environmental Protection Agency 1977, U.S. Nuclear Regulatory Commission 1980a, 1980c). Exposure may be limited or prevented by controlling and stabilizing the tailings piles. The goal is to reduce radiation emanation to as near background levels as possible. A wet or moist tailings pile or overburden prevents wind pick-up of particulates (believed to be nuclides of thorium-230, radium-226, polonium-210, and lead-210).

The radon-222 itself produces only about 5% of the radiation dose (alpha energy) that contributes to the biological hazard. The main hazard comes from the radon daughters. These daughter products of radon and thorium are electrically charged when formed and tend to attach themselves to the dust particles normally present in the atmosphere (U.S. Environmental Protection Agency 1977). Thus, they become the only significant natural radionuclides leading to widespread exposure through inhalation. Because more than one nuclide is involved, a total energy unit was developed. This unit, the working level (WL), was also designed to be a safe occupational level of exposure for miners. When this standard was first developed, a uranium miner could work in an atmosphere containing one WL. This safe level has now been reduced to one-third WL.

One WL is defined as any mixture of short half-life radon daughters in a liter of air which will ultimately produce $1.3 \times 10^5$ MeV (million electron volts) of alpha energy. Also, 100 pCi of radon-222 per liter of air, in equilibrium with its short half-life daughters, will produce $1.3 \times 10^5$ MeV of alpha energy or 1 WL of exposure. Further, a miner who worked 8 hours per day, 5 days per week, for 1 month (based on 173 hours of exposure), in a 1-WL atmosphere, would receive one working level-month (WLM) exposure. Thus, this same exposure for 1 year would be 12 WLM, which was originally considered a safe yearly occupational exposure. A person working on the surface of a tailings pile with natural surface ventilation probably would be exposed to considerably less, for example, than 1 WLM of exposure. According to Schiager (1974 ) average, annual, outdoor, radon progeny concentrations exceeding 0.003 WL in addition to background are very unlikely because of dispersion in the atmosphere and the lack of time available for development of radon daughters.

The WL of each tailings pile or mine spoil dump should be evaluated. A variety of health physics equipment—respirators, geiger-mueller and scintillation probes, dosimeters, etc.—are available to monitor and limit the worker exposure and contamination.

In August 1970, the Public Health Service provided guidance to the State of Colorado (10 CFR 712) concerning gamma radiation and radon daughter exposures. The guidance provided for an upper level, above which remedial action was suggested; an intermediate level where corrective action was based on further evaluation of the specific location; and a lower level below which no action was believed necessary. The working level guidance values were 0.05 WL and 0.01 WL above background, and the gamma radiation values were 0.1 MR per hour and 0.05 MR per hour above background, upper and lower guides, respectively. At the active tailings pond, at the Jackpile Mine, Laguna, N. Mex., the gamma value recorded on the geiger counter was 0.4 mR per hour (uncorrected for background). At an inactive tailings pile (San Mateo Mine Site, Mt. Taylor Ranger District), an average gamma value of 0.2 mR per hour (uncorrected) was recorded. These values indicate that these materials pose a clear health risk and must be handled with care.

Summary of available estimated radiation dose rates in the U.S. from all sources (U.S. Environmental Protection Agency 1977) indicates that, next to ore mining and milling (at 100,000 mrem per year), the largest doses of 140 to 14,000 mrem per year taken through the pulmonary area can be derived from inactive uranium mill tailings piles. In contrast, the average individual dose from medical and dental x-rays is 103 mrem per year.

According to the USDA Radiological Safety Handbook (Kwast and Roberts 1975), background radiation should be maintained at an acceptable level in a radiological environment, and persons younger than 18 years old and, whenever practical, women of childbearing age, should not be assigned to work with radiation. Maximum permissable exposure to radiation workers in restricted areas are specified in 10 CFR 20, as follows:

| | | Rems per calendar quarter | Millirems per 40-hour week |
|---|---|---|---|
| A. | Whole body; head and trunk active blood-forming organs; lens of eyes or gonads | 1.25 | 100 |
| B. | Hands and forearms; feet and ankles | 18.75 | 1,442 |
| C. | Skin of whole body | 7.50 | 577 |

Unless specific exceptions are approved by the USDA Radiological Safety Committee, the maximum permissable whole body exposure limit for USDA radiation workers shall not exceed 25 millirems per 40-hour week (Kwast and Roberts 1975). Recent standards developed by the U.S. Environmental Protection Agency (40 CFR 190) limit annual dose commitments to offsite individuals to 25 mrem per year or less (doses to whole body or single organ, excluding doses from radon and its daughter products). As of March 1975, the U.S. Environmental Protection Agency has adopted the policy (41 FR 28409) of assuming a linear relationship between population exposures to ionizing radiation and its biological effect. In summary, it says that there is some potential ill health attributable to any exposure to ionizing radiation and that the magnitude of potential ill health is directly proportional to the magnitude of the dose received. Thus, the linear hypothesis (all radiation is potentially harmful) by itself precludes the development of acceptable levels of risk based solely on health considerations (U.S. Environmental Protection Agency 1977).[5]

Some degree of exposure to radioactivity above normal background radiation may be inevitable to persons within uranium waste disposal areas. Because there

[5] *The Rocky Mountain Forest and Range Experiment Station takes no position on health and radiological effects of exposures to uranium mill tailings.*

are no official guidelines on exposure limits for uranium reclamation workers, these limits may have to be developed by U.S. Nuclear Regulatory Commission or U.S. Environmental Protection Agency.[6] Radiological research by agencies of the U.S. Department of Agriculture requires, at its outset, a review of the research program by the Radiological Safety Staff, Science and Education Department, U.S. Department of Agriculture. Approval to proceed with uranium mill tailings revegetation research programs is granted only if the proposed program adequately addresses the following safety criteria:[7] (1) radiation surveys and sampling to be conducted, (2) training and experience of employees relative to radiological and toxic hazards of exposure to uranium and its daughters, (3) the plan to keep exposures to uranium and its daughters to a minimum, (4) personal hygiene requirements of employees (protective clothing, respirators, and eating, drinking, and smoking only in designated areas), (5) proper methods of decontamination, (6) bioassay procedures to be used, and (7) the design and operation of any ventilation systems.

## LITERATURE CITED


Abt, Steven R., and James F. Ruff. 1978. Three procedures for estimating erosion from construction areas. p. 87-102. *In* Uranium mill tailings management, Volume II: Proceedings of a symposium. [Fort Collins, Colo., November 20-21, 1978] 141 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Alldredge, A. W., and F. W. Whicker. 1972. A method for measuring soil erosion and deposition with beta particle attenuation. Journal of Range Management 25(5):393-398.

Arthur, W. J., III, and A. W. Alldredge. 1979. Soil ingestion by mule deer in north-central Colorado. Journal of Range Management 32(1):67-71.

Breslin, A. J., and H. Glauberman. 1970. Investigation of radioactive dust dispersed from uranium tailings pile. p. 249-253. *In* Environmental surveillance in the vicinity of nuclear facilities. William C. Reinig, editor. Proceedings of a symposium sponsored by the Health Physics Society, XVI. 465 p. Charles C. Thomas, Springfield, Ill.

Butler, A. P., Jr. 1972. Uranium. p. 315-317. *In* Geologic atlas of the Rocky Mountain Region. 331 p. Rocky Mountain Association of Geologists, Denver, Colo.


*[6]According to David R. Dreesen (written communication), dose models developed by Argonne National Laboratory (U.S. Nuclear Regulatory Commission 1979b, 1980c) will aid in the assessment of health hazard to revegetation workers. U.S. Environmental Protection Agency (Office of Radiation Programs, Las Vegas Facility) also has expertise in this area.*

*[7]Written communication from Robert D. Jarrett, Radiological Safety Officer, Beltsville, Maryland, (August 26, 1980) on file at the Rocky Mountain Forest and Range Experiment Station's Research Work Unit at Rapid City, S. Dak.*


Campbell, W. F., and E. A. Rechel. 1979. *Tradescantia*, a "super-snooper" of radioactivity from uranium mill wastes. Utah Science 40(4):101-103. Utah Agricultural Experiment Station, Utah State University, Logan, Utah.

Cannon, Helen L. 1962. The development of botanical methods of prospecting for uranium on the Colorado Plateau. p. 1-50. *In* Botanical prospecting for uranium on the Colorado Plateau. U.S. Geological Survey Bulletin 1085, 188 p. Washington, D.C.

Cataldo, D. A., D. Paine, C. E. Cushing, R. M. Emery, and B. E. Vaughan. 1977. Radionuclide transport, Chapter V. p. 5.1-6.13. *In* Ecology of the 200 area plateau waste management environs: A status report. L. E. Rogers and W. H. Rickard, editors. 118 p. Battelle Pacific Northwest Laboratories, Richland Wash. [Accession Number PNL-2253, UC-11, National Technical Information Service, Springfield, Va.]

Cember, Herman. 1969. Introduction to health physics. 422 p. Pergamon Press, Oxford, England.

Chappell, W. R. 1975. Transport and biological effects of molybdenum in the environment. p. 167-188. *In* Heavy metals in the aquatic environment. P. A. Krenkel, editor. Proceedings of the International Symposium. [Nashville, Tenn., December 1973] 352 p. Pergamon Press, Oxford, England.

Chepil, W. S. 1945. Dynamics of wind erosion. Nature of movement of soil by wind. Soil Science 60:305-320. Initiation of soil movement. Soil Science 60:397-411. The transport capacity of the wind. Soil Science 60:475-480.

Clements, W. E., S. Barr, and M. L. Margle. 1978. Uranium mill tailings pile as sources of atmospheric $Rn^{222}$. p. 1559-1583. *In* Proceedings of the Natural Radiation Environment III Symposium, Volumes I and II. [Houston, Tex., April 23-28, 1978] 1789 p. (In press).

Cline, J. F. 1979. Biobarriers used in shallow burial ground stabilization. 15 p. Battelle Pacific Northwest Laboratory, Richland, Wash. [Accession Number PNL-2918, UC-70, National Technical Information Service, Springfield, Va.]

Cline, J. F., and V. A. Uresk. 1979. Revegetation of disturbed grounds in the semi-arid climate of south-central Washington. Health Physics 36:289-294.

Cline, J. F., and V. A. Uresk. 1977. Revegetation of a waste disposal site in the 200 areas of the Hanford Reservation. 16 p. Battelle Pacific Northwest Laboratories, Richland, Wash. [Accession Number PNL-2454, UC-11, National Technical Information Service, Springfield, Va.]

Cline, J. F., K. A. Gano, and L. E. Rogers. 1980. Loose rock as biobarriers in shallow land burial. Health Physics 36:497-504.

Dean, K. C., and R. Havens. 1971. Stabilizing mineral wastes. Engineering and Mineral Journal 172(4): 99-103.

Dollahite, J. W., L. D. Rowe, L. M. Cook, D. Hightower, E. M. Mailey, and J. R. Kyzar. 1972. Copper deficiency and molybdenosis intoxication associated with grazing near a uranium mine. The Southwestern Veterinarian 26(1):47-50.

Douglas, Richard L. 1977. Radiological survey at the inactive uranium mill site near Riverton, Wyoming. Technical Note ORP/LV-77-2. Office of Radiation Programs, U.S. Environmental Protection Agency, Las Vegas Facility, Las Vegas, Nev.

Dreesen, David R., M. Lynn Marple, and N. Ed Kelley. 1978. Contaminant transport, revegetation, and trace element studies at inactive uranium mill tailings piles. p. 111-140. *In* Uranium mill tailings management, Volume I: Proceedings of a symposium. [Fort Collins, Colo., November 20-21, 1978] 172 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Eadie, Gregory G., Robert F. Kaufmann, David J. Markley, and Roosevelt Williams. 1976. Report of ambient outdoor radon and indoor radon progeny concentrations during November 1975 at selected locations in the Grants Mineral Belt, New Mexico. Technical Note ORP/LV-76-4. Office of Radiation Programs, U.S. Environmental Protection Agency, Las Vegas Facility, Las Vegas, Nev.

Ellison, L. 1946. The pocket gopher in relation to soil erosion on mountain range. Ecology 27:101.

Ettershank, George, Ned Z. Elkins, Perseu F. Santos, Walter G. Whitford, and Earl F. Aldon. 1978. The use of termites and other soil fauna to develop soils on strip-mine spoils. USDA Forest Service Research Note RM-361, 4 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Evans, Kent A., E. W. Uhleman, and P. A. Eby. 1978. Atlas of western surface-mined lands: Coal, uranium and phosphate. 302 p. NALCO Environmental Sciences, Northbrook, Ill. [Accession Number FWS/OBS-78/20, U.S. Department of Interior, Fish and Wildlife Service, Washington, D.C.]

Farmer, Eugene E., and Bland Z. Richardson. 1976. Hydrologic and soil properties of coal mine overburden piles in southeastern Montana. p. 120-130. *In* Fourth Symposium on Surface Mining and Reclamation. [Louisville, Ky., October 19-21, 1976] 276 p. National Coal Association and Bituminous Coal Research, Inc.

Ford, Bacon and Davis Utah, Inc. 1976. Phase II - Title I engineering assessment of inactive uranium mill tailings, Vitro Site, Salt Lake City, Utah. 295 p. Salt Lake City, Utah [Accession Number TID-27118, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977a. Phase II - Title I engineering assessment of inactive uranium mill tailings, Shiprock Site, Shiprock, New Mexico. 209 p. Salt Lake City, Utah. [Accession Number GJT-2, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977b. Phase II - Title I engineering assessment of inactive uranium mill tailings, Mexican Hat Site, Mexican Hat, Utah. 167 p. Salt Lake City, Utah. [Accession Number GJT-3, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977c. Phase II - Title I engineering assessment of inactive uranium mill tailings, Monument Valley Site, Monument Valley, Arizona. 173 p. Salt Lake City, Utah. [Accession Number GJT-4, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977d. Phase II - Title I engineering assessment of inactive mill tailings, Tuba City Site, Tuba City, Arizona. 175 p. Salt Lake City, Utah. [Accession Number GJT-5, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977e. Phase II - Title I engineering assessment of inactive uranium mill tailings, Durango Site, Durango, Colorado. 202 p. Salt Lake City, Utah. [Accession Number GJT-6, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977f. Phase II - Title I engineering assessment of inactive uranium mill tailings, Slick Rock Sites, Slick Rock, Colorado. 196 p. Salt Lake City, Utah. [Accession Number GJT-7, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977g. Phase II - Title I engineering assessment of inactive uranium mill tailings, Naturita Site, Naturita, Colorado. 153 p. Salt Lake City, Utah. [Accession Number GJT-8, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977h. Phase II - Title I engineering assessment of uranium mill tailings, Grand Junction Site, Grand Junction, Colorado. 196 p. Salt Lake City, Utah. [Accession Number GJT-9, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977i. Phase II - Title I engineering assessment of inactive uranium mill tailings, New and Old Rifle Sites, Rifle, Colorado. 234 p. Salt Lake City, Utah. [Accession Number GJT-10, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977j. Phase II - Title I engineering assessment of inactive uranium mill tailings, Maybell Site, Maybell, Colorado. 255 p. Salt Lake City, Utah [Accession Number GJT-11, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977k. Phase II - Title I engineering assessment of inactive uranium mill tailings, Gunnison Site, Gunnison, Colorado. 237 p. Salt Lake City, Utah. [Accession Number GJT-12, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977l. Phase II - Title I engineering assessment of inactive uranium mill tailings, Phillips/United Nuclear Site, Ambrosia Lake, New Mexico. 151 p. Salt Lake City, Utah. [Accession Number GJT-13, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977m. Phase II - Title I engineering assessment of inactive uranium mill tailings, Green River Site, Green River, Utah. 153 p. Salt Lake City, Utah. [Accession Number GJT-14, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977n. Phase II - Title I engineering assessment on inactive uranium mill tailings, Spook Site, Converse County, Wyoming. 142 p. Salt Lake City, Utah. [Accession Number GJT-15, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977o. Phase II - Title I engineering assessment of inactive uranium mill tailings, Falls City Site, Falls City, Texas. 168 p. Salt Lake City, Utah. [Accession Number GJT-16, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977p. Phase II - Title I engineering assessment of inactive uranium mill tailings, Lowman Site, Lowman, Idaho. 133 p. Salt Lake City, Utah. [Accession Number GJT-17, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1977q. Phase II - Title I engineering assessment of inactive uranium mill tailings, Lakeview Site, Lakeview, Oregon. 152 p. Salt Lake City, Utah. [Accession Number GJT-18, U.S. Energy Research and Development Administration, Oak Ridge, Tenn.]

Ford, Bacon and Davis Utah, Inc. 1977r. Phase II - Title I engineering assessment of inactive uranium mill tailings, Riverton Site, Riverton, Wyoming. 156 p. Salt Lake City, Utah. [Accession Number GJT-19, National Technical Information Service, Springfield, Va.]

Ford, Bacon and Davis Utah, Inc. 1978. Laboratory research on tailings stabilization methods and their effectiveness in radiation containment. 112 p. Salt Lake City, Utah. [Accession Number GJT-21, National Technical Information Service, Springfield, Va.]

Froelich, Albert J., and Frank J. Kleinhampl. 1962. Botanical prospecting for uranium in the Deer Flat Area, White Canyon District, San Juan County, Utah. p. 51-84. In Botanical prospecting for uranium on the Colorado Plateau. U.S. Geological Survey Bulletin 1085, 188 p. Washington, D.C.

Gee, G. W., Armand Bauer, and R. S. Decker. 1978. Physical analysis of overburden materials and mine land soils. p. 665-686. *In* Reclamation of drastically disturbed lands. Frank W. Schaller and Paul Sutton, editors. 742 p. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wis.

Gee, G. W., A. C. Campbell, B. E. Opitz, and D. R. Sherwood. 1980. Interaction of uranium mill tailings leachate with Morton Ranch clay liner and soil material. p. 333-352. *In* Uranium mill tailings management. Symposium on uranium mill tailings management. [Fort Collins, Colo., November 24-25, 1980] 573 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Gilley, J. E., G. W. Gee, A. Bauer, W. O. Willis, and R. A. Young. 1977. Runoff and erosion characteristics of surface mined sites in western North Dakota. Transactions of the American Society of Agricultural Engineers 20(4):697-700, 704.

Granger, H. C. 1963. Mineralogy. p. 21-37. *In* Geology and technology of the Grants Uranium Region. V. C. Kelley, compiler. Memoir 15, 277 p. New Mexico Bureau of Mines and Mineral Resources, Socorro, N. Mex.

Hartley, J. N., P. L. Keohmstedt, and D. J. Esterl. 1979. Asphalt emulsion sealing of uranium mill tailings. p. 157-170. *In* Uranium mill tailings management. Proceedings of the second symposium. [Fort Collins, Colo., November 19-20, 1979] 331 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Havens, R., and K. C. Dean. 1969. Chemical stabilization of the uranium tailings at Tuba City, Arizona. Report of Investigation 7288, 12 p. U.S. Department of Interior, Bureau of Mines, Salt Lake City, Utah.

Haywood, F. F., W. A. Goldsmith, P. M. Lautz, W. F. Fox, W. H. Shinpaugh, and H. M. Hubbard, Jr. 1979. Assessment of the radiological impact of the inactive uranium mill tailings at Shiprock, New Mexico. 86 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Number ORNL-5447, National Technical Information Service, Springfield, Va.]

Haywood, F. F., W. A. Goldsmith, B. S. Ellis, H. M. Hubbard, Jr., W. F. Fox, and W. H. Shinpaugh. 1980a. Assessment of the radiological impact of the inactive uranium mill tailings at Mexican Hat, Utah. 86 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Number ORNL-5448, National Technical Information Service, Springfield, Va.]

Haywood, F. F., D. J. Christian, K. D. Chou, B. S. Ellis, D. Lorenzo, and W. H. Shinpaugh. 1980b. Radiological survey of the inactive uranium mill tailings at Spook Site, Converse County, Wyoming. 65 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Number ORNL-5460, UC-41, National Technical Information Service, Springfield, Va.]

Haywood, F. F., D. L. Lorenzo, D. J. Christian, K. D. Chou, B. S. Ellis, and W. H. Shinpaugh. 1980c. Radiological survey of the inactive uranium mill tailings at Riverton, Wyoming. 52 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Number ORNL-5461, National Technical Information Service, Springfield, Va.]

Headlee, T. J., and G. A. Dean. 1908. The mound-building prairie ant (*Pogonomyrex occidentalis* Cressau). Kansas State Agricultural Experiment Station Bulletin 154, 165-180. Manhattan, Kans.

Holm, W. M. 1977. Radium in consumer products on historical perspective. p. 118-121. *In* Radioactivity in consumer products. A. Alan Moghissi, Peter Paras, Melvin W. Carter, Robert F. Barker, editors. 509 p. [Accession Number PB-288743, National Technical Information Service, Springfield, Va. or Accession Number NUREG-CP-0001, Georgia Institute of Technology, Atlanta, Ga.]

International Atomic Energy Agency. 1976. Management of wastes from the mining and milling of uranium and thorium ores. Safety Series No. 44, STI/PUB/457, 49 p. Vienna, Austria.

Johansen, C. 1978. Effect of plant age on element concentrations in parts of Desmodium intortum cv. greenleaf. Communications in Soil Science and Plant Analysis 9(4):279-297.

Kalkwarf, D. R. 1979. Solubility classification of airborne products from uranium ores and tailings piles. 70 p. Battelle Pacific Northwest Laboratories, Richland Wash. [Accession Number NUREG/CR-0530, National Technical Information Service, Springfield, Va.]

Kaufmann, Robert F., Gregory G. Eadie, and Charles R. Russell. 1976. Effects of uranium mining and milling on ground water in the Grants Mineral Belt, New Mexico. Ground Water 14(5):296-308.

Kelley, Nathan Edmund. 1979. Vegetational stabilization of uranium spoil areas, Grants, New Mexico. 96 p. Ph.D. dissertation, University of New Mexico, Albuquerque. [Accession Number LA-7624-T, National Technical Information Service, Springfield, Va.]

Kleinhampl, Frank J. 1962. Botanical prospecting for uranium on South Elk Ridge, San Juan County, Utah. p. 105-188. *In* Botanical prospecting for uranium on the Colorado Plateau. U.S. Geological Survey Bulletin 1085, 188 p. Washington, D.C.

Kleinhampl, Frank J., and Carl Koteff. 1962. Botanical prospecting for uranium in the Circle Cliffs Area, Garfield County, Utah. p. 85-104. *In* Botanical prospecting for uranium on the Colorado Plateau. U.S. Geological Survey 1085, 188 p. Washington, D.C.

Kuchler, A. W. 1964. Potential natural vegetation of the coterminous United States. American Geographical Society Special Publication 36, 776 p. New York, N.Y.

Kwast, C. Z., and H. Roberts, Jr. 1975. Radiological safety handbook. 61 p. U.S. Department of Agriculture, Agricultural Research Service, Radiological Safety Staff, Beltsville, Md.

Lindsey, D. L., W. A. Cress, and E. F. Aldon. 1977. The effects of endomycorrhizae on growth of rabbitbrush, fourwing saltbrush, and corn in coal mine spoil material. USDA Forest Service Research Note RM-343, 6 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

Ludeke, Kenneth L. 1977. Tailing reclamation. p. 262-276. *In* Reclamation and use of disturbed land in the Southwest. John L. Thomas, editor. 362 p. University of Arizona Press, Tucson, Ariz.

Lusby, G. C., and T. J. Toy. 1976. An evaluation of surface mine spoils area restoration in Wyoming using rainfall simulation. Earth Surface Processes 1:375-386.

Macbeth, Paul, George Wehmann, Burton Thamer, and Darrel Card. 1979. Evaluation of alternative methods for the disposal of low-level radioactive wastes. 168 p. Ford, Bacon and Davis Utah, Inc., Salt Lake City, Utah. [Accession Numbers NUREG/CR-0680 and FBDU-209-03, National Technical Information Center, Springfield, Va.]

Markos, Gergely. 1979. Geochemical mobility and transfer of contaminants in uranium mill tailings. p. 55-70. *In* Uranium mill tailings management. Proceedings of the second symposium. [Fort Collins, Colo., November 19-20, 1979] 331 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Marple, M. L., S. Barr, and D. R. Dreesen. 1978. Biomedical and environmental research program of the LASL Health Division. Progress Report LA-7254-PR:96-100. Los Alamos Scientific Laboratory, Los Alamos, New Mex.

May, M. 1973. Reclamation of uranium-mined areas in the United States. p. 223-230. *In* Ecology of resource degradation and renewal. M. J. Chadwick and G. T. Goodman, editors. Fifteenth Symposium of the British Ecological Society. [July 10-12, 1972] 480 p. John Wiley and Sons, New York, N.Y.

Merritt, R. C. 1971. The extractive metallurgy of uranium. 576 p. Colorado School of Mines Research Institute. Johnson Publishing Co., Boulder, Colo.

Mills, M. T., R. C. Dahlman, and J. S. Olson. 1974. Ground level air concentration of dust particles downwind from a tailings area during a typical windstorm. 65 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Number N75-17842, National Technical Information Service, Springfield, Va.]

Miner, Sidney. 1969. Air pollution aspects of radioactive substances. Technical Report U7003, 159 p. Litton Systems, Inc., Bethesda, Md. [Accession Number Pb-188 092, National Technical Information Service, Springfield, Va.]

Misaqi, F. L. 1976. U.S. uranium mines and mills emit negligible radium. Mining Engineering 28(8):47.

Moffett, D., and M. Tellier. 1978. Radiological investigations of an abandoned uranium tailings area. Journal of Environment Quality 7(3):310-314.

Moffett, D., and M. Tellier. 1977. Uptake of radioisotopes by vegetation growing on uranium tailings. Canadian Journal of Soil Science 57(4):417-424.

Murray, D., and D. Moffett. 1977. Vegetating the uranium mine tailings at Elliot Lake, Ontario. Journal of Soil and Water Conservation 32(4):171-174.

National Academy of Sciences. 1974. Rehabilitation potential of western coal lands. 198 p. Balinger Publishing Co., Cambridge, Mass.

Nelson, R. William, Glendon W. Gee, and Clarence A. Oster. 1980. Radon control by multilayer earth barriers. p. 79-88. *In* Uranium mill tailings management. Symposium on uranium mill tailings management. [Fort Collins, Colo., November 24-25, 1980] 573 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Nielson, R. F., and H. B. Peterson. 1978. Vegetating mine tailings ponds. p. 645-652. *In* Reclamation of drastically disturbed lands. Frank W. Schaller and Paul Sutton, editors. 742 p. American Society of Agronomy, Madison, Wis.

Nielson, R. F., and H. B. Peterson. 1973. Establishing vegetation on mine tailings waste. p. 103-115. *In* Ecology and reclamation of devastated lands, Volume II. Russell J. Hutnik and Grant Davis, editors. 504 p. Gordon and Breach, New York, N.Y.

Nielson, R. F., and H. B. Peterson. 1972. Treatment of mine tailings to promote vegetative stabilization. Bulletin 485, 22 p. Agriculture Experiment Station, Utah State University, Logan, Utah.

Packer, Paul E., and Earl F. Aldon. 1978. Revegetation techniques for dry regions. p. 425-450. *In* Reclamation of drastically disturbed lands. Frank W. Schaller and Paul Sutton, editors. 742 p. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wis.

Peterson, H. B., and R. F. Nielson. 1973. Toxicities and deficiencies in mine tailings. p. 15-25. *In* Ecology and reclamation of devastated land, Volume I. Russell J. Hutnik and Grant Davis, editors. 538 p. Gordon and Breach, New York, N.Y.

Rahn, Perry H. 1975. Ground water in coal strip-mine spoils, Powder River Basin. p. 348-361. *In* Proceedings of the Fort Union Coal Field Symposium, Volume III. 706 p. [Billings, Mont., April 25-26, 1975] Montana Academy of Sciences, Eastern Montana College, Billings, Mont.

Rapaport, Irving. 1963. Uranium deposits of the Poison Canyon Ore Trend, Grants District. p. 122-135. *In* Geology and technology of the Grants Uranium District. Memoir 15, 277 p. New Mexico Bureau of Mines and Mineral Resources. Socorro, N. Mex.

Reed, A. K., H. C. Meeks, S. E. Pomeroy, and V. Q. Hale. 1976. Assessment of environmental aspects of uranium mining and milling. 50 p. Battelle Columbus Laboratories, Columbus, Ohio. [Accession Numbers PB 266413 and EPA-600/7-76-036, National Technical Information Service, Springfield, Va.]

Reynolds, Jack F., Michael J. Cwik, and N. Ed Kelley. 1978. Reclamation at Anaconda's open pit uranium mine, New Mexico. Reclamation Review 1:9-17. Pergamon Press, New York, N.Y.

Rickard, W. H., et al. 1977. Radioecology of uranium. p. 4.28-4.41. *In* B. E. Vaughn and staff members, Pacific Northwest Laboratory Annual Report for 1976 to the ERDA Assistant Administrator for Environment and Safety. 131 p. Battelle Pacific Northwest Laboratories, Richland, Wash. [Accession Number BNWL-2100 PTZ/UC-11, National Technical Information Service, Springfield, Va.]

Rogers, V. C., R. F. Overmyer, and K. K. Nielson. 1979. Radon attenuation through cover materials. p. 145-156. *In* Uranium mill tailings management. Proceedings of the second symposium. [Fort Collins, Colo., November 19-20, 1979] 331 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Rogers, L. E., and W. H. Rickard, editors. 1977. Ecology of the 200 area plateau waste management environs: A status report. 118 p. Batelle Pacific Northwest Laboratories, Richland, Wash. [Accession Number PNL-2253/UC-11, National Technical Information Service, Springfield, Va.]

Romney, E. M., W. A. Rhoads, A. Wallace, and R. A. Wood. 1973. Persistence of radionuclides in soil, plants and small mammals in areas contaminated with radioactive fallout. p. 170-176. *In* Radionuclides in ecosystems. D. J. Nelson, editor. 687 p. [Accession Number CONF-710501-PL, National Technical Information Service, Springfield, Va.]

Rosenfield, J., and O. A. Beath. 1964. Selenium—geobotany, biochemistry, toxicity, and nutrition. Academic Press, New York, N.Y.

Sandoval, F. M., and W. L. Gould. 1978. Improvement of saline- and sodium-affected disturbed lands. p. 485-504. *In* Reclamation of drastically disturbed lands. Frank W. Schaller and Paul Sutton, editors. 742 p. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wis.

Scarano, Ross A., and John J. Linehan. 1978. Current U.S. Nuclear Regulatory Commission licensing review process: Uranium mill tailings management. p. 3-14. *In* Uranium mill tailings management, Volume I. Proceedings of a symposium. [Fort Collins, Colo., November 20-21, 1978] 172 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Schaller, Frank W., and Paul Sutton, editors. 1978. Reclamation of drastically disturbed lands. 742 p. American Society of Agronomy, Madison, Wis.

Schiager, K. J. 1974. Analysis of radiation exposure on or near uranium mill tailings piles. Radiation Data and Reports 15(7):375-476. Office of Radiation Programs, U.S. Environmental Protection Agency.

Schilling, John H. 1971. Open-pit mining. p. 2-4. *In* Survey of surface mining in New Mexico. By John H. Schilling, Will W. Baltosser, George B. Griswold, Walter K. Wagner, Lucien A. File, Edward C. Beaumont, Frank E. Kottlowski, and Don H. Baker, Jr. Circular 114, 17 p. Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology. Socorro, N. Mex.

Schreckhise, R. G., R. M. Emery, L. E. Rogers, L. L. Cadwell, J. F. Cline, R. E. Fitzner, K. A. Gano, T. M. Poston, and W. H. Pickard. 1979. Radioecology of nuclear fuel cycles. p. 5.17-5.23. *In* Pacific Northwest Laboratory Annual Report for 1978 to the DOE Assistant Secretary for Environment, Part 2 Ecological Sciences. 175 p. Battelle Pacific Northwest Laboratory, Richland, Wash. [Accession Number PNL-2850, UC-11, National Technical Information Service, Springfield, Va.]

Schreckhise, R. G., and J. F. Cline. 1980. Uptake and distribution of 232 in peas and barley. Health Physics 38:341-343.

Schwendiman, L. C., G. A. Sehmel, T. W. Horst, C. W. Thomas, and R. W. Perkins. 1979. Field and modeling study of wind blown particles from a uranium mill tailings pile. 128 p. Battelle Pacific Northwest Laboratories, Richland, Wash. [Accession Numbers PNL-2890 and NUREG/CR-0629, National Technical Information Service, Springfield, Va.]

Sehmel, G. A. 1977. Wind erosion research at an uranium mill tailings site. 10 Aerosol Technology Meeting. [Albuquerque, N. Mex., September 26, 1977] 5 p. Battelle Northwest Laboratory, Richland, Wash. [Accession Numbers CONF-7709192-1, and BNWL-6447, National Technical Information Service, Springfield, Va.]

Seton, E. T. 1929. Lives of game animals. 4:395-418. Doubleday, Doran and Co., Garden City, N.Y.

Shepherd, Thomas A., and John D. Nelson. 1978. Long-term stability of uranium mill tailings. p. 155-172. *In* Uranium mill tailings management, Volume I. Proceedings of a symposium. [Fort Collins, Colo., November 20-21, 1978] 172 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Soholt, Lars F., William K. Irwin, and Michael R. Griffin. 1976. Effect of rodent burrowing on physical properties of a soil in the Mojave Desert of southern Nevada. Bulletin of the Ecological Society of America, 1976 Annual Meeting, 57(1):14. New Orleans, La.

Squyres, J. B. 1970. Origin and depositional environment of uranium deposits of the Grants Region, New Mexico. Ph.D. dissertation, Stanford University, Palo Alto, Calif.

State of North Dakota. 1978. Final west-central North Dakota regional environmental impact study on energy development. 266 p. Bureau of Land Management, Bismarck, N. Dak.

Tennessee Valley Authority. 1976. Final environmental statement Morton Ranch uranium mining. 288 p. Tennessee Valley Authority, Chattanooga, Tenn.

Tennessee Valley Authority. 1978. Final environmental statement Dalton Pass uranium mine, Volume I and II. 432 p. Tennessee Valley Authority, Chattanooga, Tenn.

Tennessee Valley Authority. 1979. Draft environmental statement Edgemont Uranium Mine. 193 p. Tennessee Valley Authority, Chattanooga, Tenn.

Thames, John L., editor. 1977. Reclamation and use of disturbed land in the Southwest. 362 p. The University of Arizona Press, Tucson, Ariz.

Thames, J. L., R. T. Patten, and E. J. Crompton. 1974. Hydrologic study of a reclaimed surface mined area on the Black Mesa. p. 106-116. *In* Second research and applied technology symposium on mined land reclamation. Coal and the Environment Technical Conference. [Louisville, Ky., October 22-24, 1974] 252 p.

Thorne, D. W., and H. B. Peterson. 1949. Irrigated soils their fertility and management. 288 p. The Blakiston Co., Philadelphia and Toronto.

Travis, C. C., A. P. Watson, L. M. McDowell-Boyer, S. J. Cotter, M. L. Randolph, and D. E. Fields. 1979. A radiological assessment of radon-222 released from uranium mills and other technologically enhanced sources. 216 p. Oak Ridge National Laboratory, Oak Ridge, Tenn. [Accession Numbers NUREG/CR-0573, ORNL/NUREG-55, National Technical Information Service, Springfield, Va.]

Uresk, D. W., and J. F. Cline. 1978. Decommissioning and decontamination studies. p. 8.7-8.9. *In* B. E. Vaughn and staff members, Pacific Northwest Laboratory Annual Report for 1977 to the DOE Assistant Secretary for Environment, Part 2 Ecological studies. 100 p. Battelle Pacific Northwest Laboratories, Richland, Wash. [Accession Numbers PNL-2500 PT2/UC-11, National Technical Information Service, Springfield, Va.]

USDA Forest Service. 1979a. User guide to vegetation mining and reclamation in the West. 85 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

USDA Forest Service. 1979b. User guide to soils mining and reclamation in the West. 80 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

USDA Forest Service. 1979c. User guide to engineering mining and reclamation in the West. 58 p. Intermountain Forest and Range Experiment Station, Ogden, Utah.

U.S. Department of Energy. 1979. Annual status report on the inactive uranium mill tailings sites remedial action program. 202 p. Environmental Control Technology Division, Office of Environmental Compliance and Overview. [Accession Number DOE/EV-0060, UC-2, 11, National Technical Information Service, Springfield, Va.]

U.S. Energy Research and Development Administration. 1976. National uranium resource evaluation, preliminary report. 132 p. Grand Junction, Colo. [Accession Number GJO-111(76), Bendix Field Engineering Corporation, Grand Junction, Colo.]

U.S. Environmental Protection Agency. 1973. Environmental evaluation of Mines Development, Inc. —Uranium and vanadium milling operations at Edgemont, South Dakota. Report Number SA/TSB-18, 58 p. U.S. Environmental Protection Agency, Denver, Colo. [Accession Number PB-256453, National Technical Information Service, Springfield, Va.]

U.S. Environmental Protection Agency. 1976. Drinking water regulations, radionuclides. Federal Register 133, Volume 41, July 9, 1976.

U.S. Environmental Protection Agency. 1977. Radiological quality of the environment in the United States, 1977. EPA-520/1-77-009. 295 p. Office of Radiation Programs, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1979a. Draft generic environmental impact statement on uranium milling. Project M-25, NUREG-0511, Volume I, Summary and Text. 346 p. U.S. Nuclear Regulatory Commission, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1979b. Draft generic environmental impact statement on uranium milling. Project M-25, NUREG-0511, Voume II, Appendices. 225 p. U.S. Nuclear Regulatory Commission, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1980a. Final generic environmental impact statement on uranium milling. Project M-25, Summary and Text, NUREG-0706, Volume I. 361 p. U.S. Nuclear Regulatory Commission, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1980b. Final environmental impact statement on uranium milling. Project M-25, Appendices A-F, NUREG-0706, Volume II. 226 p. U.S. Nuclear Regulatory Commission, Washington, D.C.

U.S. Nuclear Regulatory Commission. 1980c. Final environmental impact statement on uranium milling. Project M-25, Appendices G-V, NUREG-0706, Volume III. 161 p. U.S. Nuclear Regulatory Commission, Washington, D.C.

Utah Water Research Laboratory. 1976. Erosion control during highway construction, final report. Volumes I, II, III, NCHRP Project 16-3. Utah Water Research Council, Utah State University, Logan, Utah.

Vavilov, P. O., B. I. Gruzder, V. I. Maslov, V. Ya. Ovehentor, and A. I. Taskaer. 1977. Results of an experiment over many years in decontaminating radium-bearing and uranium radium-bearing pollutants in the central Taiga. The Soviet Journal of Ecology 8(6):496-500.

Verma, T. R., and J. L. Thames. 1978. Grading and shaping for erosion control and vegetative establishment in dry regions. p. 399-409. *In* Reclamation of drastically disturbed lands. Frank W. Schaller and Paul Sutton, editors. 742 p. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wis.

Whicker, F. Ward. 1978. Biological interactions and reclamation of uranium mill tailings. p. 141-154. *In* Uranium mill tailings management, Volume I. Proceedings of a symposium. [Fort Collins, Colo., November 20-21, 1978] 172 p. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Fort Collins, Colo.

Wijk, H. F. Van, and R. Braams. 1960. Incorporation of caesium-137 from nucleus debris into the biosphere. Nature 188:951-952.

Wood, J. M. 1974. Biological cycles for toxic elements in the environment. Science 183:1049-1052.

Wullstein, L. H. 1978. Vegetative stabilization report, Appendix A. p. 1-24. *In* Laboratory research on tailings stabilization methods and their effectiveness in radiation containment. By Paul J. Macbeth, Craig M. Jensen, Vern C. Rogers, and Robert F. Overmyer. 100 p. Ford, Bacon and Davis Utah, Inc., Salt Lake City, Utah. [Accession Number GJT-21, National Technical Information Service, Springfield, Va.]

Yamamoto, Teruo. 1979. Mixing overburden to simulate soil conditions: ARCO. Black Thunder Mine, Volume II. p. 791-797. *In* Ecology and coal resource development, Volumes I and II. Mohan K. Wali, editor. 1091 p. [Based on the International Congress for Energy and the Ecosystem, Grank Forks, N. Dak., June 12-16, 1978]

Yamamoto, Teruo. 1982. A review of uranium spoil and mill tailings revegetation in the western United States. USDA Forest Service General Technical Report RM-92, 20 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

The following aspects of uranium mine and mill tailings management are reviewed and discussed: (1) the history of the uranium remedial action program, (2) magnitude of the uranium spoils problem, (3) uranium deposits, mining, and milling, (4) status of reclamation, (5) problems in revegetation of uranium spoils and tailings, and (6) health and safety conditions.

**Keywords:** Reclamation, revegetation, mining, uranium, mine spoils, mill tailings.

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Rocky Mountains

Southwest

Great Plains


U.S. Department of Agriculture
Forest Service


# Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

## RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

## RESEARCH LOCATIONS

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Albuquerque, New Mexico
Bottineau, North Dakota
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Fort Collins, Colorado*
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Lincoln, Nebraska
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*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526